THE INTERACTION OF LIVING SYSTEMS WITH THE SPACE ENVIRONMENT

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ABSTRACT

The successful launch and recovery of Biosatellite II and III was clearly a very rewarding endeavor. Thirteen experiments were flown in Biosatellite II for two days in September 1967. All of the 13 experiments were concerned with the role of gravity in living systems. Six experiments sought to determine the effects of weightlessness alone. Seven investigated the combined effects of radiation and weightlessness.

It was found that weightlessness altered the orientation as well as the growth of plants (pepper and wheat seedlings). The studies expanded the scientific knowledge of several mechanisms of plant function and growth that are regulated by gravity.

Bacteria, insects and plants exposed to gamma radiation while weightless confirmed that neutralization of gravity does change the effects of radiation on the cellular elements that control heredity. The effects were significantly selective. Greater damage occurred to unpaired chromosomes such as the "X" or male chromosome.

The primate in Biosatellite III showed physiologic deterioration attributed, mainly, to 8 1/2 days of

weightlessness. Changes occurred in central nervous system function, cardiovascular performance, fluid and electrolyte metabolism and circadian rhythms.

In general, positive effects of space flight in Biosatellites II and III were observed in cell division and differentiation, growth and development, chromosome aberrations and mechanics, mutations, biochemical interaction, and decrement physiologic function in organs and systems.

Living organisms, from microbial forms to man, are extremely responsive to their environment. The history of science shows that living systems have successfully adapted their life forms and life cycles to an inconceivable variety of Earth biologic environments. The space environment provides still another variety of unique environments to which living Earth systems are being exposed.

Looking back, the Space Science Board of the National Academy of Sciences, during its 1962 Summer Study, recommended "..... an exploitation of special features of the space environment as unique situations for the general analysis of the organism-environment relationships including, especially, the role environmental inputs play in the establishment and maintenance of normal organization (and function) in the living system."

Subsequently, in response to a NASA request, the scientific community enthusiastically submitted more than 185 experiment proposals for the Biosatellite late in 1962 and early in 1963. These were evaluated by panels of specialists and were submitted with recommendations to the Bioscience Subcommittee of the NASA Space Science Steering Committee during the fall of 1963. At the same time, the NASA Ames Research Center was selected to manage the Biosatellite Project, and began development of the recommended experiments. In early 1964 the General Electric Company was awarded the contract to design, fabricate, and test six spacecraft and associated ground equipment.

The Biosatellite is an Earth-orbiting satellite containing biologic experiments to study the effects of the space environment on living organisms. The specific factors studied were weightlessness, weightlessness combined with gamma radiation, and removal from the Earth's rotation. Originally, there were three Biosatellite missions, each with a back-up flight: a three-day mission, a 30-day mission, and

and a 21-day mission. In fiscal year 1969, the 21-day mission was cancelled and in fiscal year 1970 the second 30-day mission primate flight was dropped.

Although Biosatellite I was lost, the successful launch and recovery of Biosatellites II and III was clearly a very rewarding scientific endeavor. In Biosatellite II, the back-up of Biosatellite I, thirteen experiments were flown for two days in September 1967. All of the experiments were concerned primarily with the role of gravity in living systems. Six experiments sought to determine the effects of weightlessness alone. Seven investigated the combined effects of radiation and weightlessness.

The recent flight of Biosatellite III with a male pig-tailed monkey (Macaca nemestrina) included as its goals a comprehensive evaluation of central nervous, cardiovascular and metabolic effects of prolonged weightlessness on the primate. The flight lasted only 8 1/2 of the planned 30-days mission.

In Biosatellite II, the seven radiation-weightlessness experiments in the forward section (figure 1) were carried out with Tradescantia sp (clone 02), Habrobracon junglandis, Neurospora crassa, Tribolium confusum, larvae and adults of Drosophila melanogaster, and lysogenic bacteria (Escherichia coli and Salmonella typhimurium). Six weightlessness experiments in the after compartment (figure 2) were performed on pepper plants, wheat seedlings, fertilized frog eggs, and multinucleated amoebae. In addition, there were non-irradiated, weightless controls for each experiment in the forward section.

The effects studied by the experimenters included cell division and differentiation, development and growth, chromosome damage and mechanics, genetic mutations and biochemical regulation of cell nutrition and metabolism.

All experiment 'packages' including live specimens had experienced exposure to expected flight conditions with the exception of weightlessness prior to flight to give background data on possible responses to vibration, linear acceleration, temperature excursion, and other factors. Several sets of earth controls were run simultaneously with the flight period for comparison with flight specimens.

I will not detail all thirteen experiments since they have been documented previously. Rather, I will discuss those in which significant changes occurred. For instance it was that weightlessness altered the orientation as well as the growth of plants. In the pepper plant, Capsicum annuum, epinasty was observed in the leaves and stems by time lapse photography in the orbiting plants (figure 3)

compared to plants prior to flight. Although the degree of curvature was similar to that in clinostat control plants on Earth, no leaf motion was seen in weightless plants as occurred in both erect and clinostat controls. Return to normal Earth position of the leaves was delayed following recovery of the Biosatellite. There was no significant difference in amino acid and carbohydrate mobility in leaves and stems between the on-orbit plants and Earth clinostat controls. Both groups were significantly disoriented when compared to erect Earth controls.

When compared to Earth clinostat controls, the wheat seedlings, Triticum vulgare, germinating in the Biosatellite showed no significant difference in growth, development, morphology, energetics and auxin production and distribution. Disorientation of roots and coleoptiles was present in the weightless seedlings (figure 4) and the clinostat controls, when compared to seedlings grown erect to gravity in the Earth control laboratory.

The specific activity of peroxidase, glucose-6-phosphate dehydrogenase, and glyceraldehyde-3-phosphate dehydrogenase was higher in the tissues of flight plants than in earth clinostat and erect seedlings. Malic dehydrogenase, transminase and cytochrome-C reductase activities were not significantly different in any of the seedlings. No alterations were observed in carbohydrate, amino acid, and nitrogen content.

There was no significant difference in germination or coleoptile length. The ratio of roots to shoot were greater in the orbited seedlings as compared to earth clinostat and erect controls. Both the weightless and clinostat root tips and coleoptile tips showed a random distribution of statolith granules.

No significant effects attributable to weightlessness were observed in the developing frog eggs (figure 5) or the amoeba (figure 6).

In the weightless environment of the orbiting Biosatellite II, the radiation effects observed depended on the nature of the organism. In some cases the effects of radiation combined with weightlessness were greater than those observed in Earth-based controls and in some cases, the effects were less.

Seven hundred twenty pupae flour beetle, Tribolium confusum, (pre-irradiated with 1350 R of 180 keV x-rays) were orbitied in the Biosatellite, half in the presence of 85-strontium and half shielded from it. Identical Earth controls were maintained. Of the earth irradiated controls and the shielded flight pupae, 29.9% developed wing abnormalities (figure 7) whereas the abnormality occurred in

44.8% of the adults from flight irradiated pupae, which received an additional 100-150 R on orbit. Dominant lethality occurred in 78±6% of the offspring of flight irradiated female oocytes, compared to 27±5% in the Earth-irradiated controls.

In the vinegar gnat adults, Drosophila melanogaster, the deformed thorax and missing wing (figure 8) in Biosatellite II organisms was twice that of Earth controls. The interaction of weightlessness and gamma radiation induced premature aging and chromosome translocations and non-disjunction (extra Y's and missing Y's and IV's). Chromosome breaks were significantly increased.

The blue flower, Tradescantia, and the parasitic wasp, Habrobracon, showed cases of antagonism and enchancement of radiation-induced damage as well as no significant changes in certain parameters. The orange bread mold, Neurospora crassa, showed no changes. Antagonism of radiation by weightlessness was obvious, but not pronounced, in the lysogenic bacteria.

The experiment results of Biosatellite II showed convincingly that there is an interaction between radiation and one or more other factors encountered in flight. This interaction varied between increasing the effects of radiation fourfold to decreasing the effect slightly but significantly.

The plant experiments for study of the biologic effects of weightlessness alone showed a close correspondence to results obtained by exposure to rotation on the clinostat. The clinostat exposure, in its simplest form, consists of rotating a plant in horizontal position (normal to the direction of the force of gravity) at a rate of rotation sufficient to prevent the plant from responding normally to gravity in any one direction.

The physiologic deterioration of the primate flown in Biosatellite III is mainly attributed to the effects of weightlessness. The details are in press in SCIENCE. In summary, the monkey was in excellent condition at the time of launch and was fully adapted to restraint in his flight couch and long periods of isolation. All physiologic sensors functioned perfectly during flight and following recovery (figures 9-12).

Preliminary examination of these data indicate that the monkey remained alert in his waking periods until the eighth day. Much new information has been gathered on cycles of sleep and wakefulness in weightlessness. From brain wave records, heart rate and respiration, brain and body temperatures, and from spacecraft data on carbon dioxide excretion, it is clear that the animal lost normal circadian

or 24-hour rhythm and was no longer synchronized to the capsule day-night cycle. This longer period gave a progressive phase displacement of 8 hours in the daily peak of his metabolic and brain wave activities so that by the eighth day he slept late into the morning period. No such changes were seen prior to launch in the flight monkey nor in numerous control animals.

For the first time in any space flight of man or animals, the occurrence of rapid-eye-movement (REM) sleep was confirmed. This sleep constitutes about 20 per cent of normal sleep on earth and in man is associated with dreaming. It is essential in full amounts for continued behavioral well-being.

However, important signs of patho-physiology first appeared in early days of the flight. For the first time in man or animals, pendular eye movements were recorded in the first three days of weightlessness and indicate a vestibular-ocular disturbance. The eyes swung slowly and rhythmically from side to side about once per second with progressively increasing amplitude.

The animal's condition deteriorated sharply on the eighth day. Food and water were no longer taken during this period and the heart rate slowed to 70 beats per minute with an accompanying sharp drop in blood pressure. Brain wave records showed increased slow waves but were consistent with a sleeping rather than a comatose condition. This situation occurred at the end of a period in which the only telemetered signs of a progressive decline in general condition was a slow fall in brain temperature to 35°C compared with 38.2°C at launch, and a drop in central venous pressure (measured in the right atrium) to below 0 in the last 3 days of flight. Photographic records have confirmed that the animal was alert and active until the eighth day. Immediately prior to de-orbit the heart rate had fallen to 39 beats per minute.

The fluid loss approximating 20 per cent of body weight has been closely investigated, both from physiological data, and data on water condensed in the spacecraft. The following account of circumstances leading to the animal's collapse implicates weightlessness as a prime factor and is relevant to environmental constraints, task requirements and mission durations.

Spacecraft data clearly indicate an early and profound loss of fluid by insensible perspiration. After the fourth day this mechanism was no longer as severe. The urine output increased steadily to almost diuretic levels by the eighth day of flight making it difficult to measure calcium, creatine and creatinine excretion by virtue of a

high dilution (figures 13 and 14). As nearly as can be determined, the net negative fluid balance over the 8 day period was 1250 to 1280 milliliters. A primary mechanism of the continued loss of water in the later stages of flight appears to relate to a redistribution of blood volume in the thorax as a consequence of weightlessness.

The critical measurements from this study is the finding of a high fluid loss, even in a sedentary resting state, related to shifts in blood volume and its distribution. This involves perturbations in body fluid balance, electrolyte metabolism of sodium and potassium, and ultimately, the stability of the cardiovascular system.

In general then, the significant effects of space on the Biosatellite II experiments were observed in: (1) young and actively dividing cells **and tissues; (2) rapidly dividing** cells with a high metabolic rate; and (3) cells such as sperm and eggs after meiosis. Mature cells were least affected. Positive effects were observed in cell division and differentiation, growth and development, chromosome aberrations and mechanics, mutations, biochemical processes and population dynamics.

The Biosatellite III preliminary findings indicate positive effects of weightlessness on the central nervous system, cardiovascular system, fluid and electrolyte metabolism and altered circadian or 24-hour rhythmic cycles.

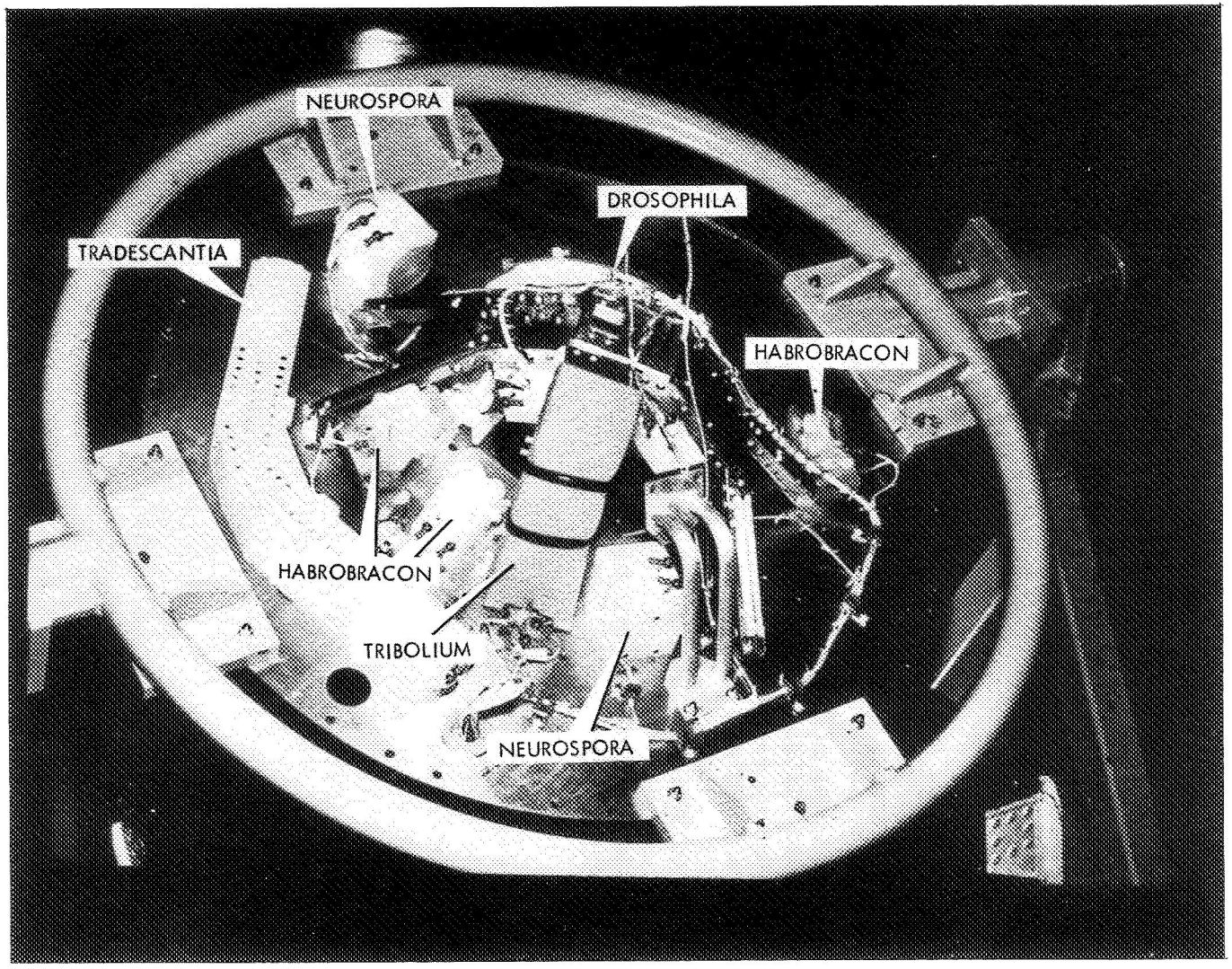

Figure 1. Biosatellite Experiments Payload Assembly (Located Around Radiation Source)

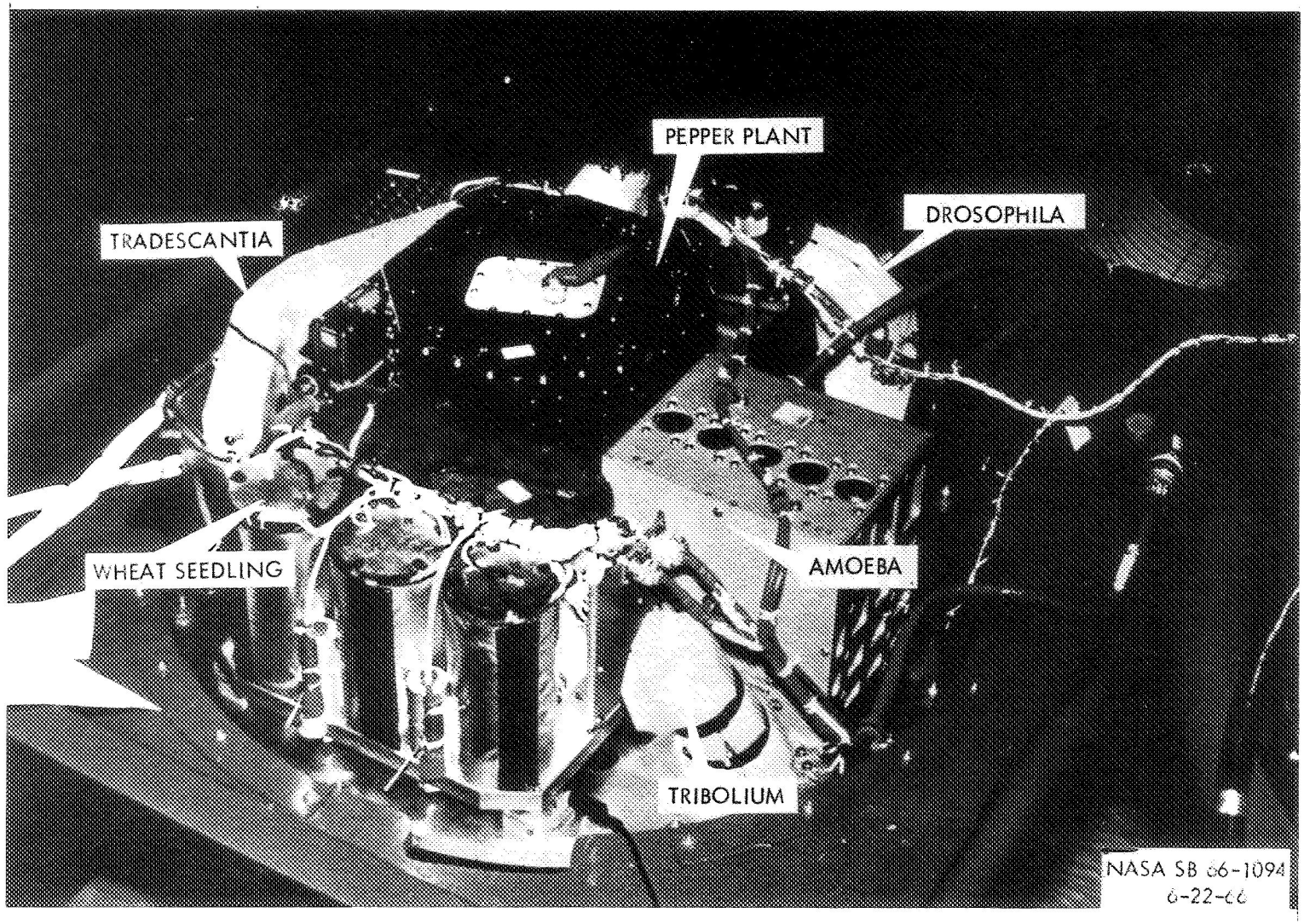

Figure 2. Biosatellite Experiments Payload Assembly (Behind Radiation Shield)

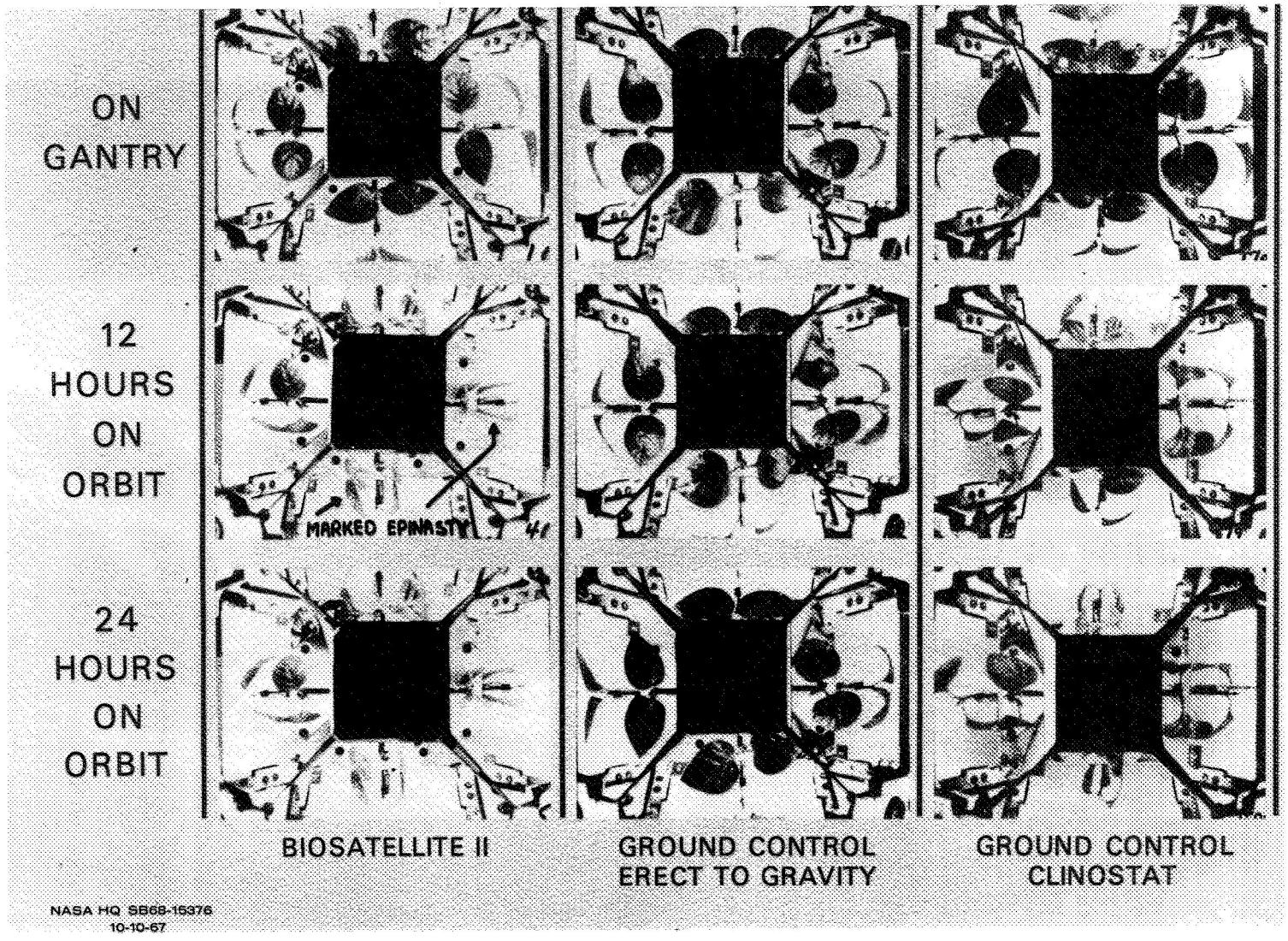

Figure 3. Biosatellite II: Effect of Weightlessness on Pepper Plant

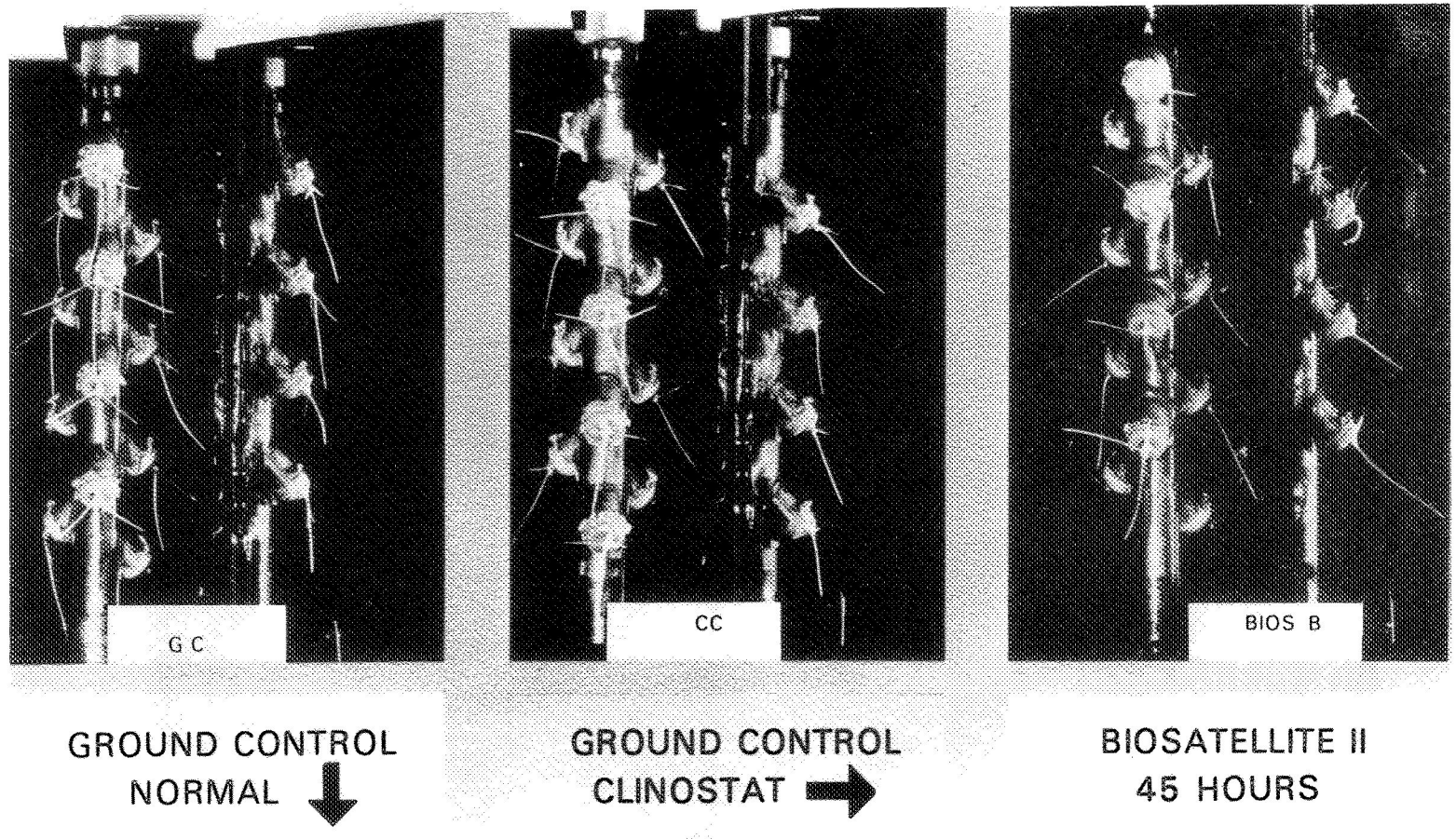

Figure 4. Biosatellite II: Effect of Weightlessness on Developing Wheat Seeds

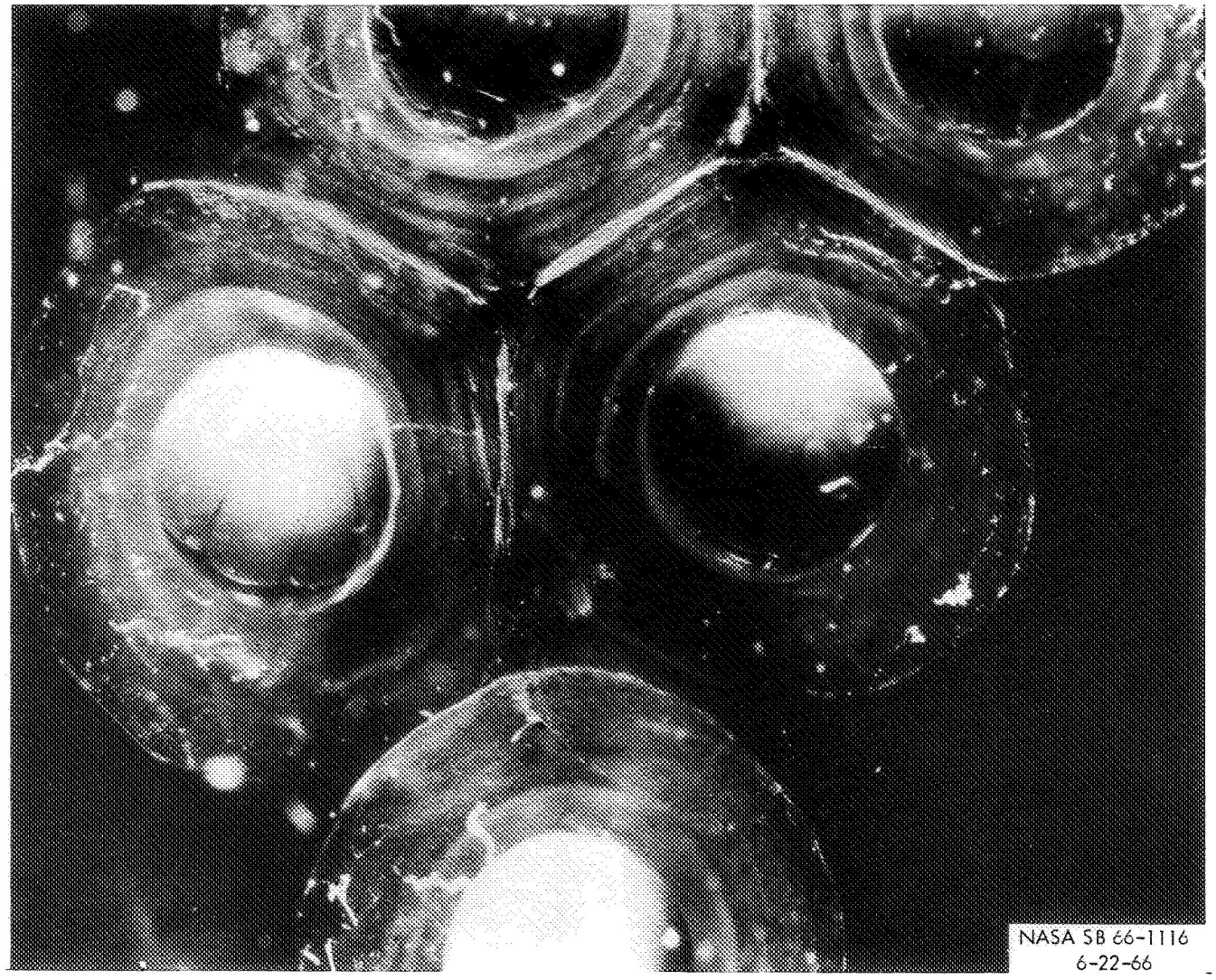

Figure 5. Frog Eggs With Eight Cells After 2.5 Hours of Weightlessness

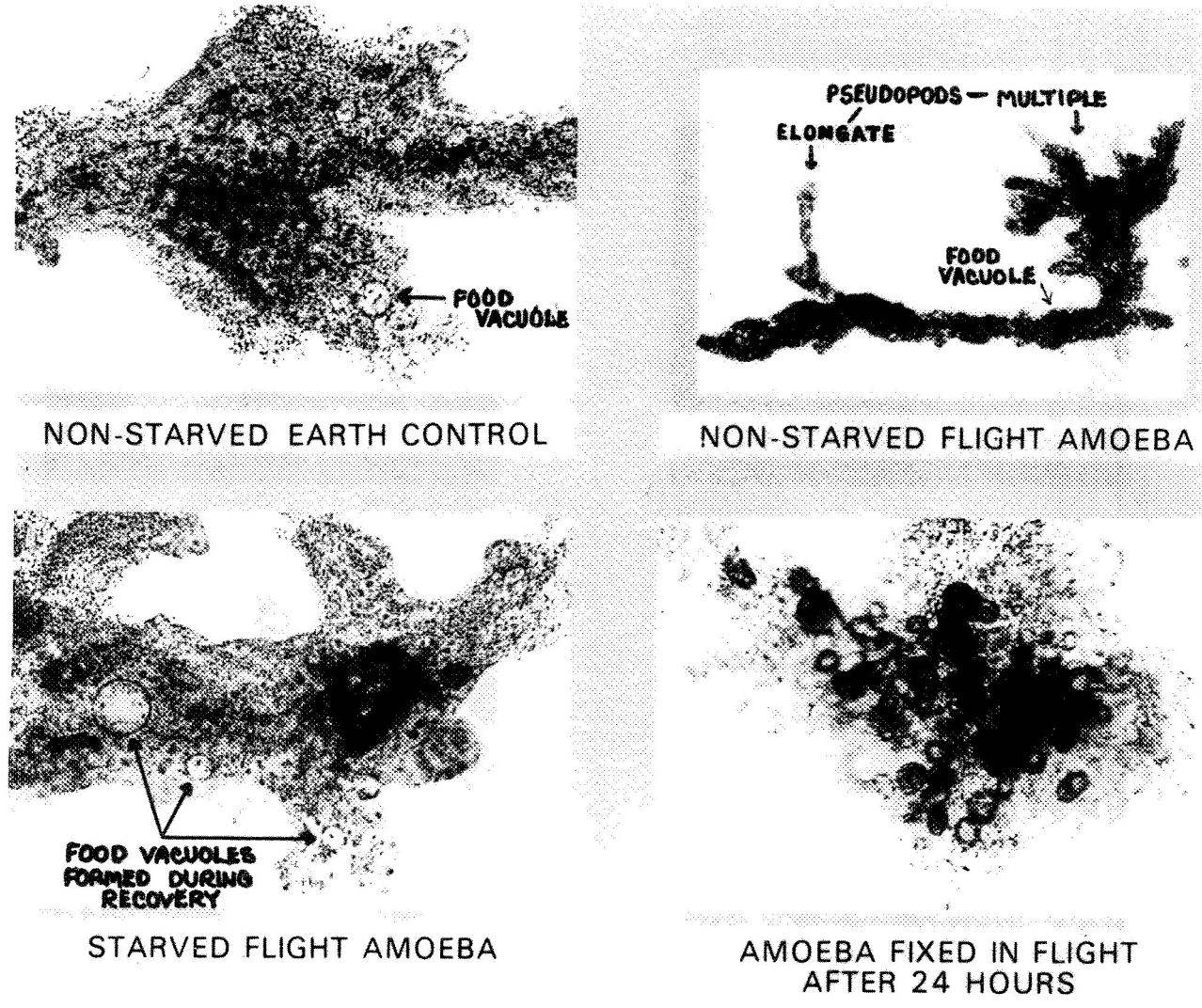

Figure 6. Biosatellite II: Effect of Weightlessness on the Amoeba

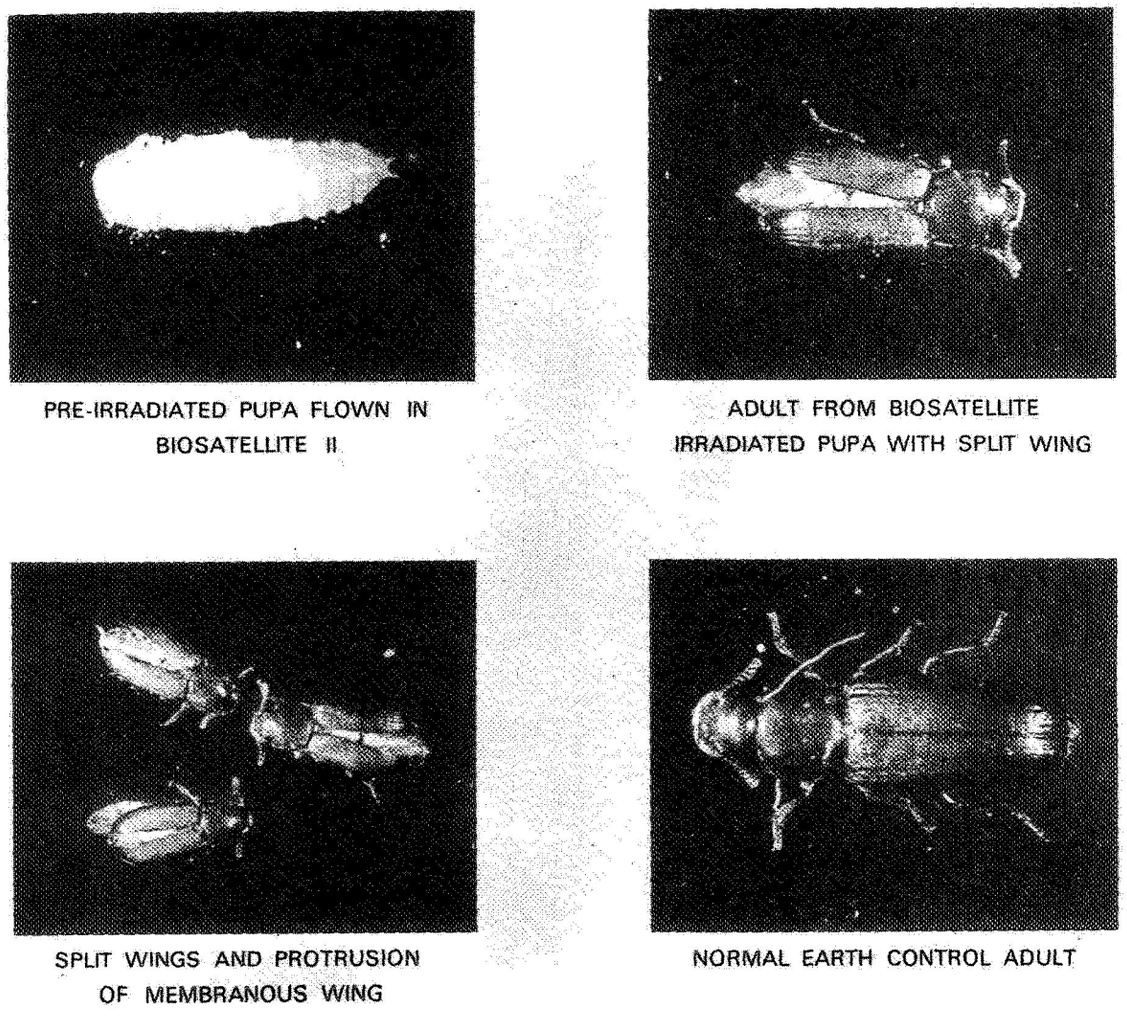
PRE-IRRADIATED PUPA FLOWN IN BIOSATELLITE II
ADULT FROM BIOSATELLITE IRRADIATED PUPA WITH SPLIT WING
SPLIT WINGS AND PROTRUSION OF MEMBRANOUS WING
NORMAL EARTH CONTROL ADULT

Figure 7. Biosatellite II: Effects of Weightlessness and Radiation on Tribolium

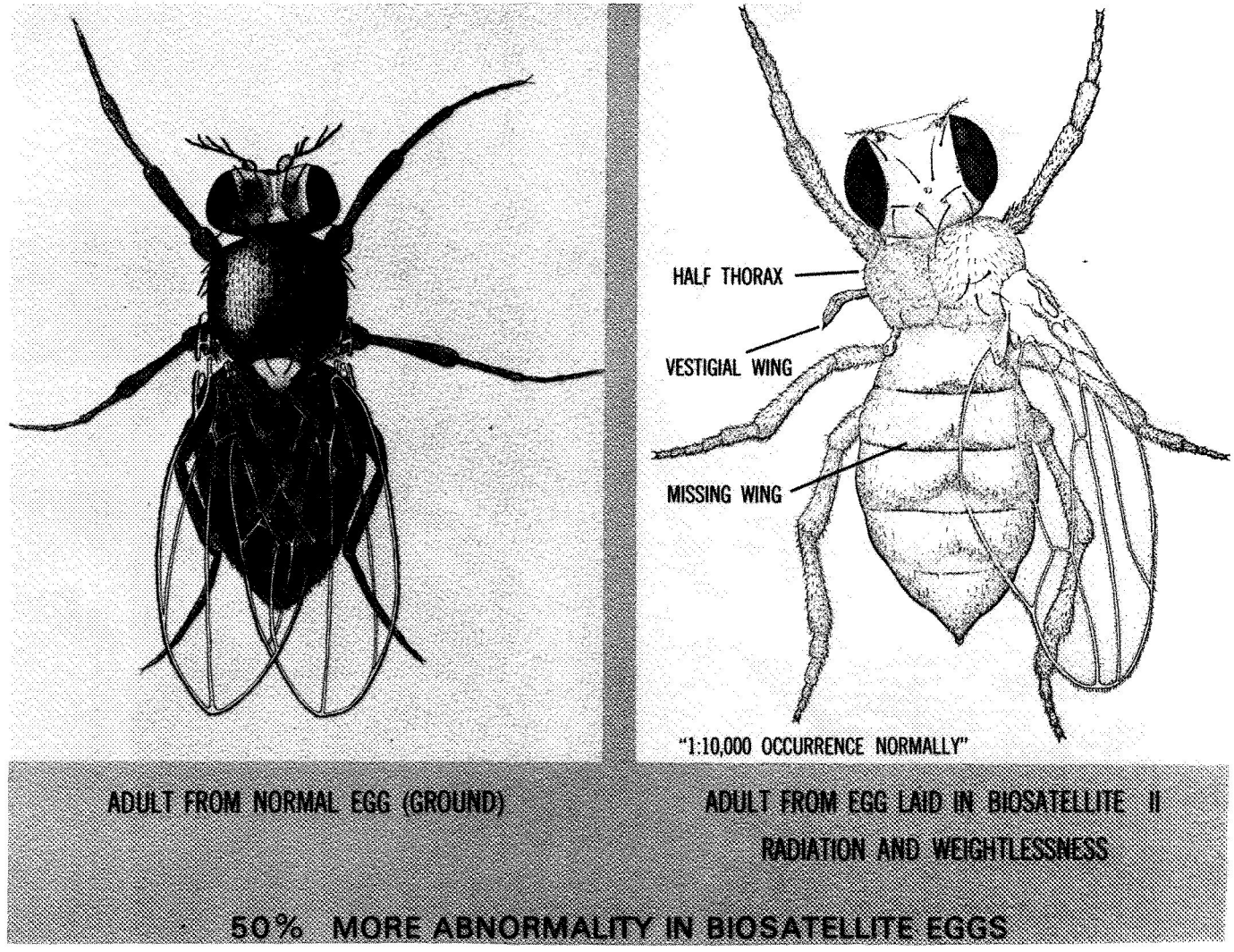

Figure 8. Biosatellite II: Effects of Radiation and Weightlessness on Drosophila (Vinegar Gnat)

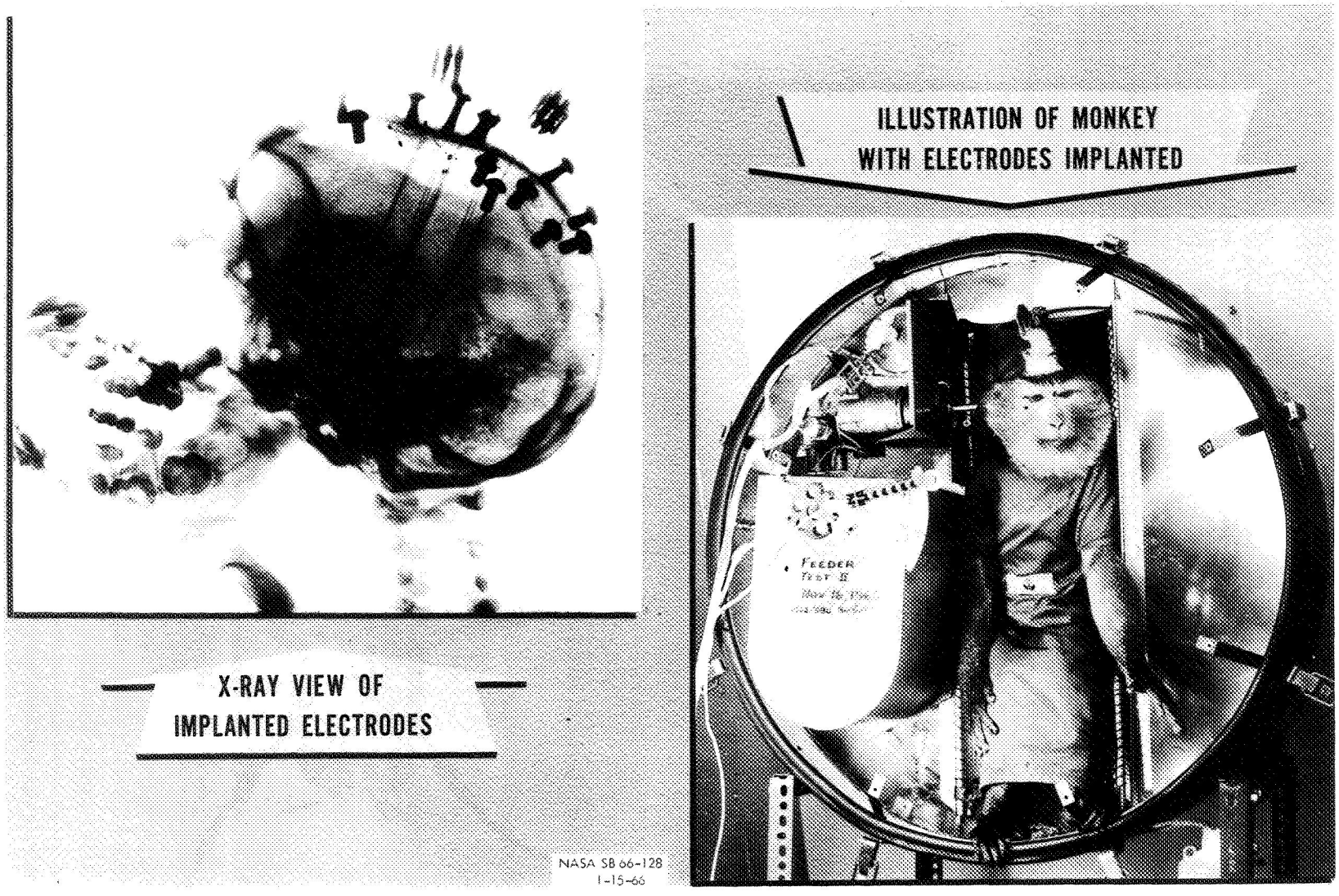

Figure 9. Brain Electrodes in Primate

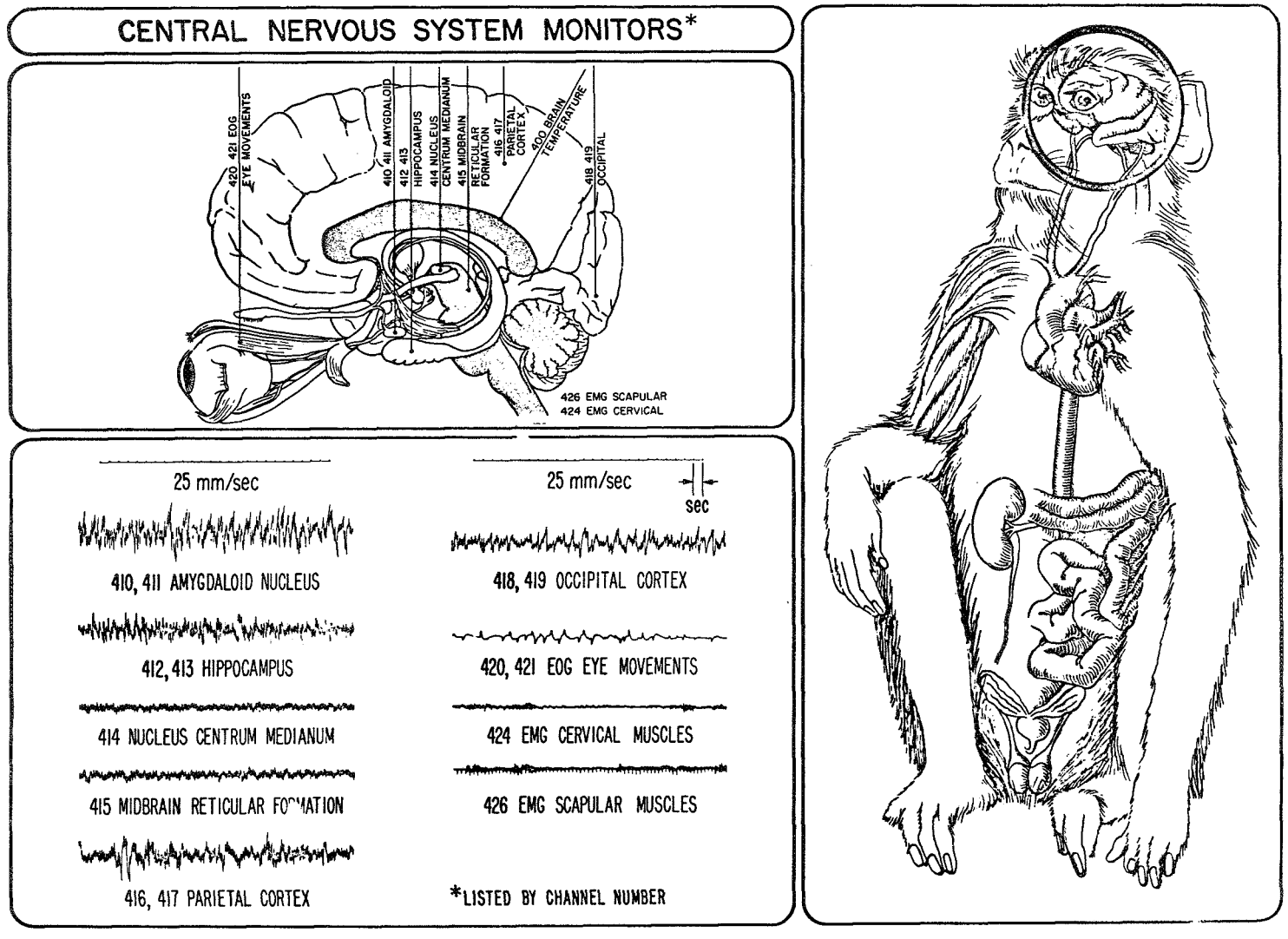
CENTRAL NERVOUS SYSTEM MONITORS*
420 421 EOG EYE MOVEMENTS
410 411 AMYGDALOID
412 413 HIPPOCAMPUS
414 NUCLEUS CENTRUM MEDIANUM
415 MIDBRAIN RETICULAR FORMATION
416 417 PARIETAL CORTEX
400 BRAIN TEMPERATURE
418 419 OCCIPITAL
426 EMG SCAPULAR
424 EMG CERVICAL
25 mm/sec
25 mm/sec
sec
410, 411 AMYGDALOID NUCLEUS
418, 419 OCCIPITAL CORTEX
412, 413 HIPPOCAMPUS
420, 421 EOG EYE MOVEMENTS
414 NUCLEUS CENTRUM MEDIANUM
424 EMG CERVICAL MUSCLES
415 MIDBRAIN RETICULAR FORMATION
426 EMG SCAPULAR MUSCLES
416, 417 PARIETAL CORTEX
*LISTED BY CHANNEL NUMBER

Figure 10

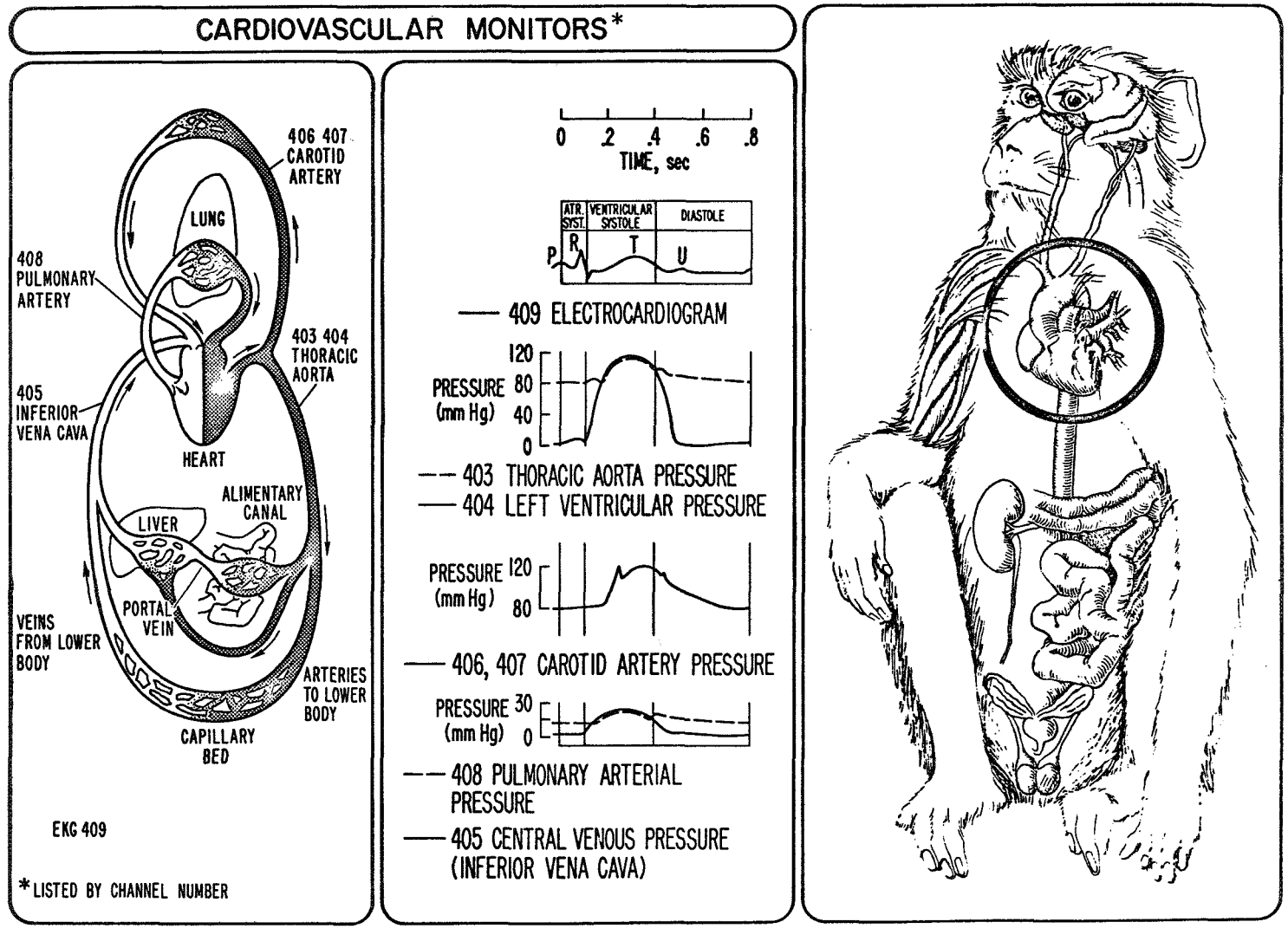
CARDIOVASCULAR MONITORS*
406 407 CAROTID ARTERY
LUNG
408 PULMONARY ARTERY
403 404 THORACIC AORTA
405 INFERIOR VENA CAVA
HEART
ALIMENTARY CANAL
LIVER
PORTAL VEIN
VEINS FROM LOWER BODY
ARTERIES TO LOWER BODY
CAPILLARY BED
EKG 409
*LISTED BY CHANNEL NUMBER
0 .2 .4 .6 .8
TIME, sec
ATR. SYST.
VENTRICULAR SYSTOLE
DIASTOLE
P R T U
409 ELECTROCARDIOGRAM
PRESSURE (mm Hg) 120 80 40 0
403 THORACIC AORTA PRESSURE
404 LEFT VENTRICULAR PRESSURE
PRESSURE (mm Hg) 120 80
406, 407 CAROTID ARTERY PRESSURE
PRESSURE (mm Hg) 30 0
408 PULMONARY ARTERIAL PRESSURE
405 CENTRAL VENOUS PRESSURE (INFERIOR VENA CAVA)

Figure 11

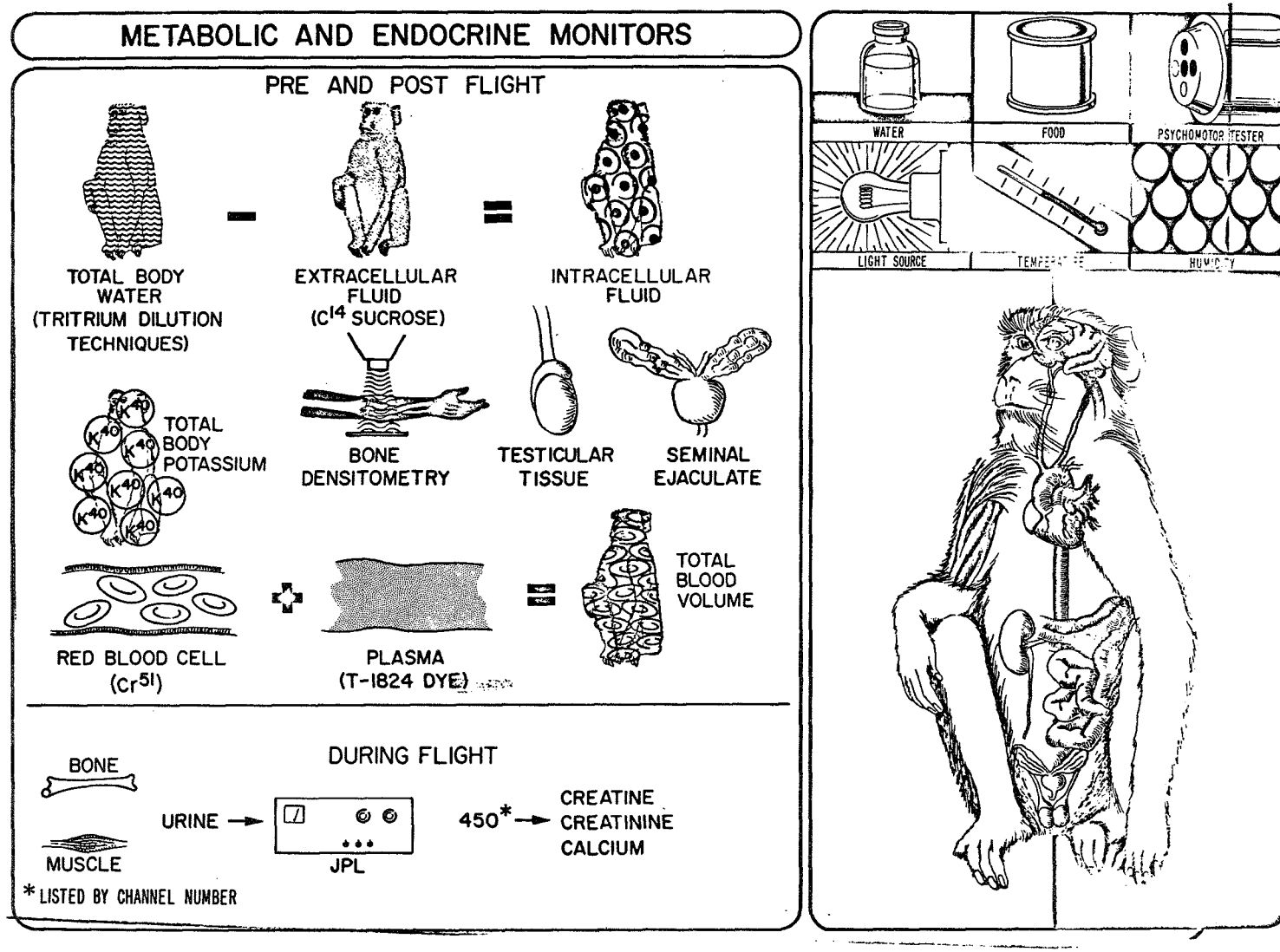
METABOLIC AND ENDOCRINE MONITORS
PRE AND POST FLIGHT
TOTAL BODY WATER (TRITRIUM DILUTION TECHNIQUES)
EXTRACELLULAR FLUID (C^{14} SUCROSE)
INTRACELLULAR FLUID
TOTAL BODY POTASSIUM
BONE DENSITOMETRY
TESTICULAR TISSUE
SEMINAL EJACULATE
RED BLOOD CELL (Cr^{51})
PLASMA (T-1824 DYE)
TOTAL BLOOD VOLUME
DURING FLIGHT
BONE
MUSCLE
URINE
JPL
450*
CREATINE
CREATININE
CALCIUM
*LISTED BY CHANNEL NUMBER
WATER
FOOD
PSYCHOMOTOR TESTER
LIGHT SOURCE

Figure 12

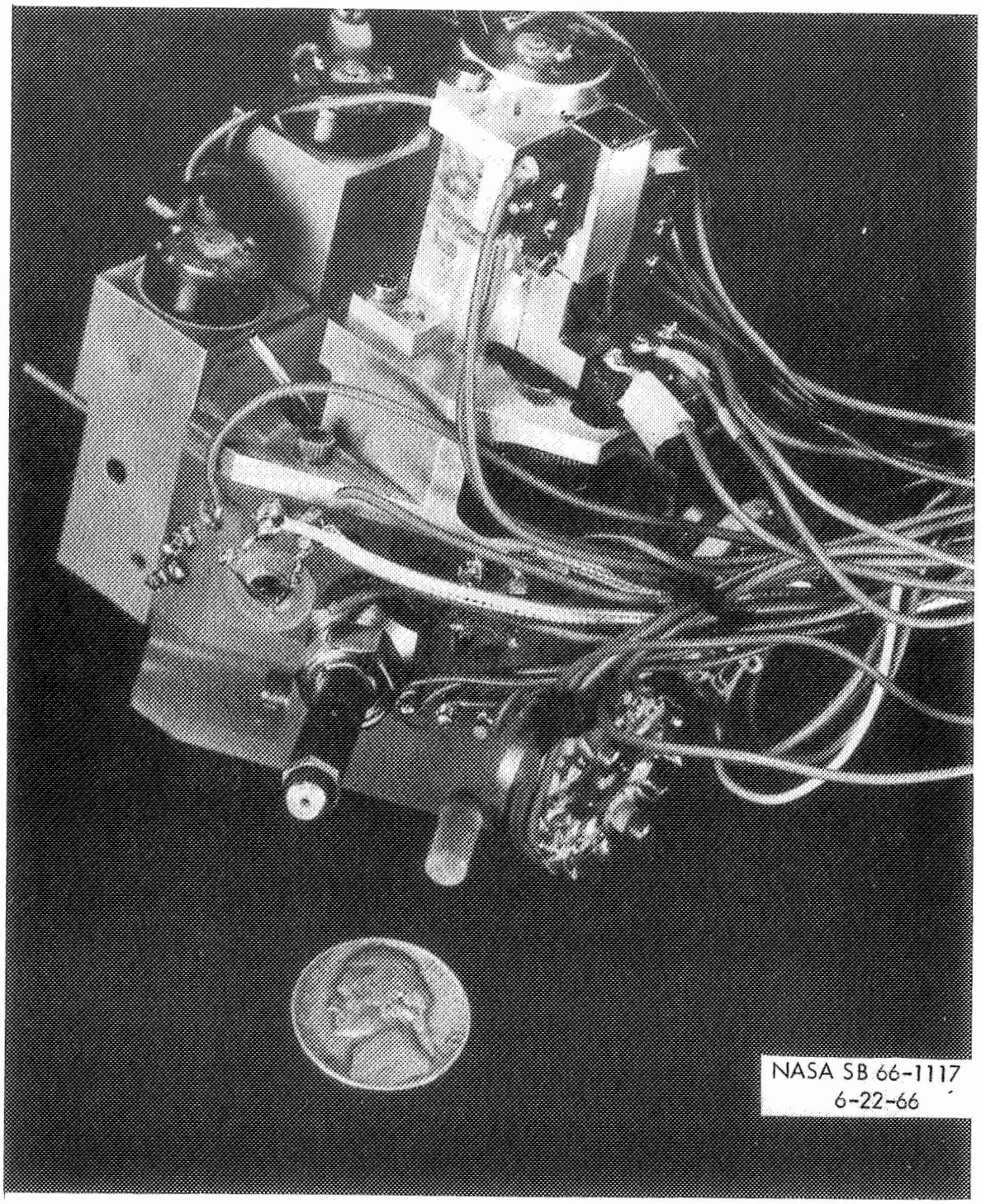

Figure 13. Biosatellite In-Flight Urinalysis System

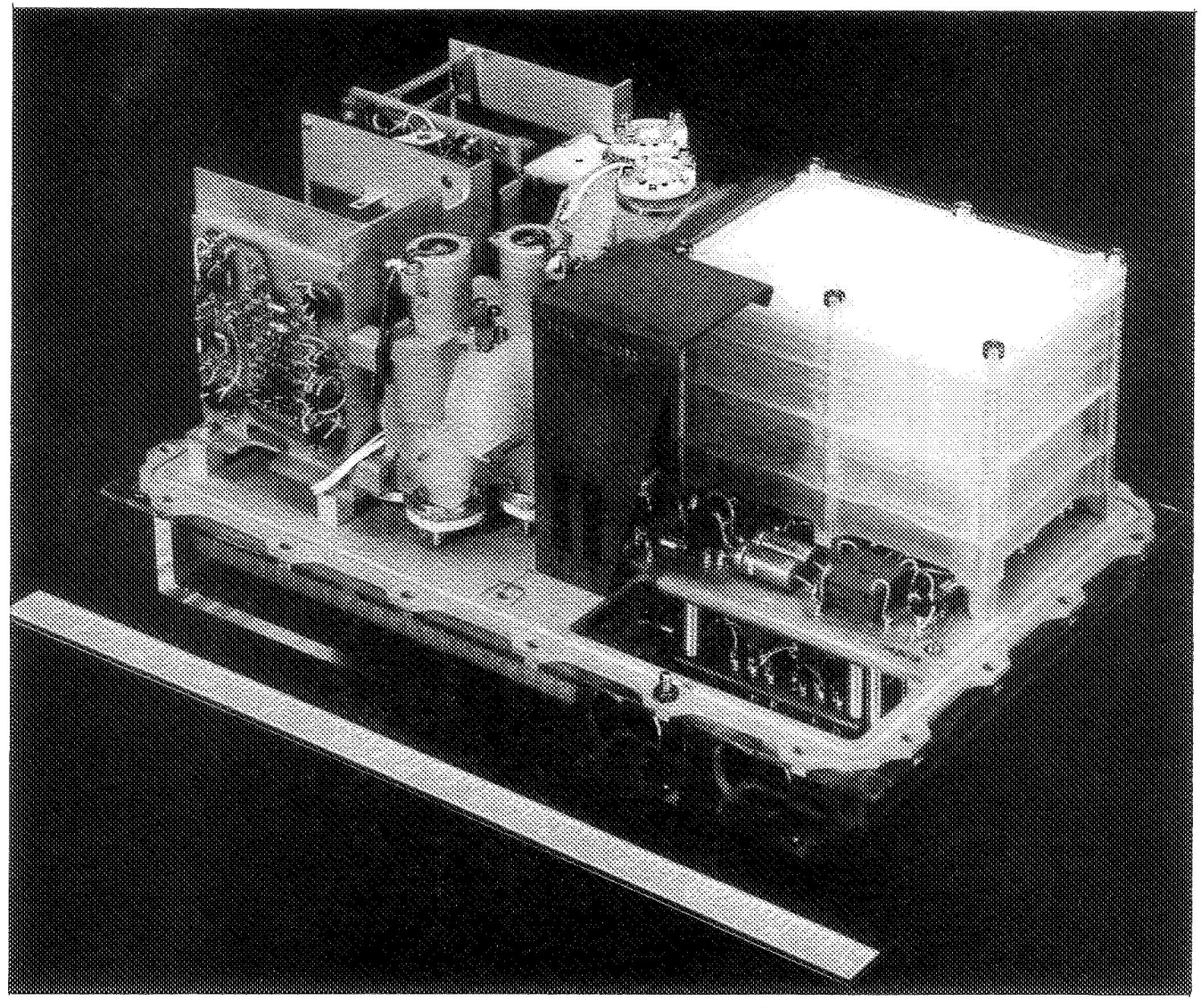

Figure 14